Improved A-Si:H TFT Pixel Electrode Circuits for Active-Matrix Organic Light Emitting Displays

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***Abstract*—Two improved four thin-film-transistors (TFTs) pixel electrode circuits based on hydrogenated amorphous silicon (a-Si:H) technology have been designed. Both circuits can provide a constant output current level and can be automatically adjusted for TFT threshold voltage variations. The circuit simulation results indicate that an excellent linearity between the output current and input current can be established. An output current level higher than $\sim$ 5 μA can be achieved with these circuits. This current level can provide a pixel electrode brightness higher than 1,000 $\mathrm{cd/m^2}$ with the organic light-emitting device (OLED) having an external quantum efficiency of 1%. These pixel electrode circuits can potentially be used for the active-matrix organic light-emitting displays (AM-OLEDs).**

I. Introduction

OVER the past few years, several efforts have been made to develop the active-matrix (AM) driving techniques for the organic light-emitting displays (OLEDs) [1]–[4]. AM-OLED driving schemes based on one thin film transistor (TFT) [1], two-TFT [2], [3], and four-TFT [4] pixel electrode circuits were proposed. It is well established that one-TFT configuration [1] cannot be used for AM-OLED because a continuous excitation cannot be achieved in this type of circuits. The two-TFT configuration [2], [3] will suffer from a nonnegligible threshold voltage (V_{th}) variation of the drive TFT due to the process variation or long-term operation. This V_{th} variation can cause brightness nonuniformity over the display panel. The four-TFT configuration [4], although partially compensates for the V_{th} variation, uses too many (four) control lines to be practicable. In addition, most of these efforts [2]–[4] were based on the polysilicon TFT technology, which is not cost effective in comparison with the amorphous silicon (a-Si) TFT technology. Recently, a four-TFT pixel electrode circuit for AM-OLED has been developed based on a-Si:H TFT technology [5]. This circuit uses only two control lines and shows an excellent electrical reliability for long-term display operation. However, its output current tends to saturate at a certain level that may be insufficient to drive the OLEDs to high brightness levels.

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In this paper, we propose two improved a-Si:H TFT based circuits that can be used for high brightness AM-OLEDs. The circuit simulation results indicate that both circuits show a very good linearity between the output and input currents. The maximum output current that can be achieved with these circuits is higher than 5 μA. Such an output current level is sufficient to provide a pixel electrode brightness in excess of $\sim$1000 $\mathrm{cd/m^2}$ for a typical OLED having an external quantum efficiency of 1%.

II. Circuit Schematic and Operation

To achieve a high output current and a good output-input current linearity, a modified four-TFT pixel electrode circuit has been designed, Fig. 1(a). In this circuit, the OLED is represented by a TFT (T5) in combination with a diode capacitance (C_{diode}) in parallel. The T5 and C_{diode} sizes were optimized to ensure that under the forward bias condition the current flow in T5-C_{diode} combination is similar to the one expected for the OLEDs. This was verified experimentally. This circuit has five external terminals (V_{DD}, ground, V_{ctrl}, I_{data}, and V_{select}) including three control lines (V_{ctrl}, I_{data}, and V_{select}). V_{DD} and g*round* (OLED cathode) terminals are common power sources connected to all pixels on the panel. A control line (V_{ctrl}) is used to control the T4 gate. V_{select} (pulsed voltage) is the scan line signal, while I_{data} (data current) is the data current signal. The operation of this circuit can be described as follows.

ON state: When the select line (V_{select}) signal is high, both T1 and T2 are turned ON. At the same time, V_{ctrl} signal is low and T4 is turned off. The data line signal (I_{data}) then passes through T1 and T2 and sets both the drain and gate voltages of T3. Consequently, the potentials at nodes A and B will allow the data current (I_{data}) to pass through T3. The T3 is working in the saturation region, e.g., $V_{\mathrm{DS}} > V_{\mathrm{GS}} - V_{\mathrm{th}}$ (threshold voltage). Because T4 is off, no current can flow through T4 from V_{DD}. Therefore, the current flowing though T3 is equal to I_{data}. This current then will turn on the T5 (e.g., representing OLED) and reach the ground.

OFF state: When the pixel circuit is deselected and the select line signal is low, both the T1 and T2 are OFF. At the same time, the V_{ctrl} signal is high to turn on T4, allowing that the current flows from V_{DD} to T3 via T4. Since V_{DD} is a high potential power source, the potential at point B will increase after the circuit is switched from ON-

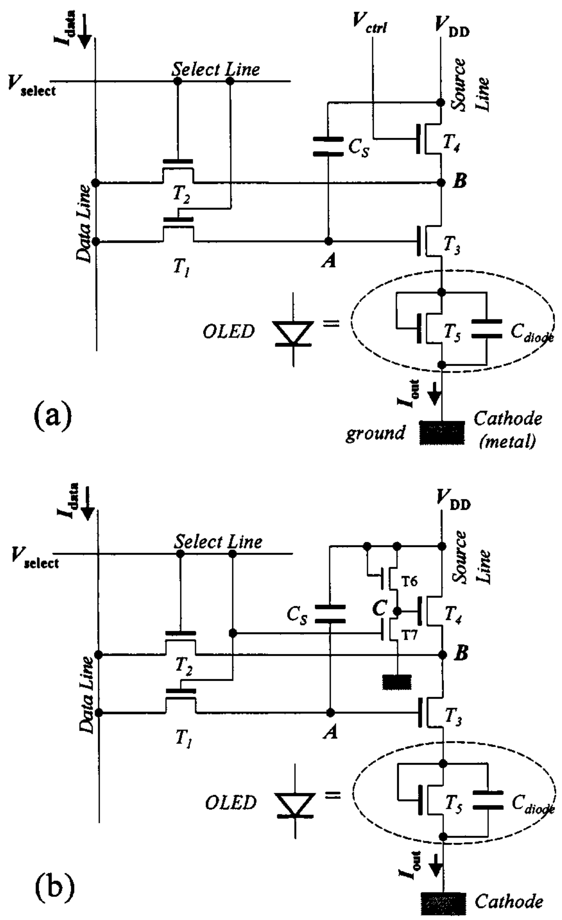

Fig. 1. (a) Constant current-source pixel electrode circuit using four TFTs and an extra terminal ($V_{\rm ctrl}$). (b) The constant current-source pixel circuit using a two-TFT based inverter. The W/L ratios for T6 and T7 are, for example, 1/6 and 10/6, respectively.

TABLE I
PIXEL ELECTRODE CIRCUIT SIMULATION PARAMETERS

V_{DD} [V]	25
V_{select} [V]	0→25
I_{data} [μA]	0→5
V_{ctrl} [V]	25→0
μ_{FE} [cm^2/V·sec]	0.25
V_{th} [V]	2.5
W_1/L_1 [μm]	50/6
W_2/L_2 [μm]	100/6
W_3/L_3 [μm]	250/6
W_4/L_4 [μm]	250/6
W_5/L_5 [μm]	200/6
W_6/L_6 [μm]	1/6
W_7/L_7 [μm]	10/6
C_{diode} [pF]	6.4
C_s [pF]	6.61
C_p [fF]	570
R_s [Ω]	100

to OFF-state. The T3 gate voltage (V_G) is maintained at the previous level by the charges stored in the storage capacitor C_s. Therefore, $V_{\rm DS}$ of T3 remains higher than $V_{\rm GS} - V_{\rm th}$ and the TFT remains in the saturation region. Consequently, the output current $(I_{\rm out})$ is maintained at the same level as in the ON-state. Thus, $I_{\rm out} = I_{\rm data}$.

A closer look at this circuit approach reveals that the signal of the $V_{\rm ctrl}$ terminal is exactly the inverse of select line signal $(V_{\rm select})$. Therefore, a two-TFT-based inverter can be added in this pixel electrode circuit to replace the $V_{\rm ctrl}$ terminal. This approach, illustrated in Fig. 1(b), will reduce the number of terminals used but increase the circuit complexity. However, the two-TFT based inverter does not have to be included in every pixel. Instead, it can be designed at the edge of the display panel or included in the driving circuit to reduce the pixel complexity. To achieve the voltage inversion, the geometrical dimensions of T6 and T7 need be optimized so that $(W_7/L_7)/(W_6/L_6) \gg 1(W_6, W_7, L_6$, and L_7 represent the channel width and length of T6 and T7, respectively). In the ON-state, $(V_{\rm select})$ will turn on T1, T2, and T7. The T6 is always on because its drain and gate are connected together. Since both T6 and T7 are on, the current flows from $V_{\rm DD}$ to ground through T6 and T7. In equilibrium, T6 and T7 will act like two resistors linked in series, and the gate voltage of T4 at node C will be determined by these two resistor and $V_{\rm DD}$ values. Since the resistance of a TFT in the on-state is proportional to its W/L ratio, the T4 gate voltage will be $\sim V_{\rm DD} \times (W_6/L_6)/(W_7/L_7) \ll V_{\rm DD}$. This voltage can be adjusted to a value smaller than the threshold voltage of T4 by choosing the appropriate W_6, W_7, L_6, and L_7 parameters. Then T4 will be off and, therefore, no current will flow through T4, as in the case of the $V_{\rm ctrl}$-line approach. In the OFF-state, T1, T2, and T7 will be turned off. The gate voltage of T4 at node C will be set high by $V_{\rm DD}$ through T6. This circuit condition will allow for the current to flow from $V_{\rm DD}$ to T3 through T4. Similar to the case of the $V_{\rm ctrl}$-line approach, the $V_{\rm DS}$ of T3 will remain higher than $V_{\rm GS} - V_{\rm th}$, and T3 will still operate in the saturation region. As a result, the output current level will be maintained constant.

III. CIRCUIT SIMULATION AND DISCUSSIONS

To support the circuit analysis, pixel electrode circuit simulation has been performed on a SUN SPARCstation-20 workstation using CADENCE SPECTRE with the a-Si:H TFT density-of-states (DOS) model [6]. The pixel electrode circuit simulation parameters are tabulated in Table I. Please note that a series resistance (R_s) of 100 Ω was applied on all the lines. All

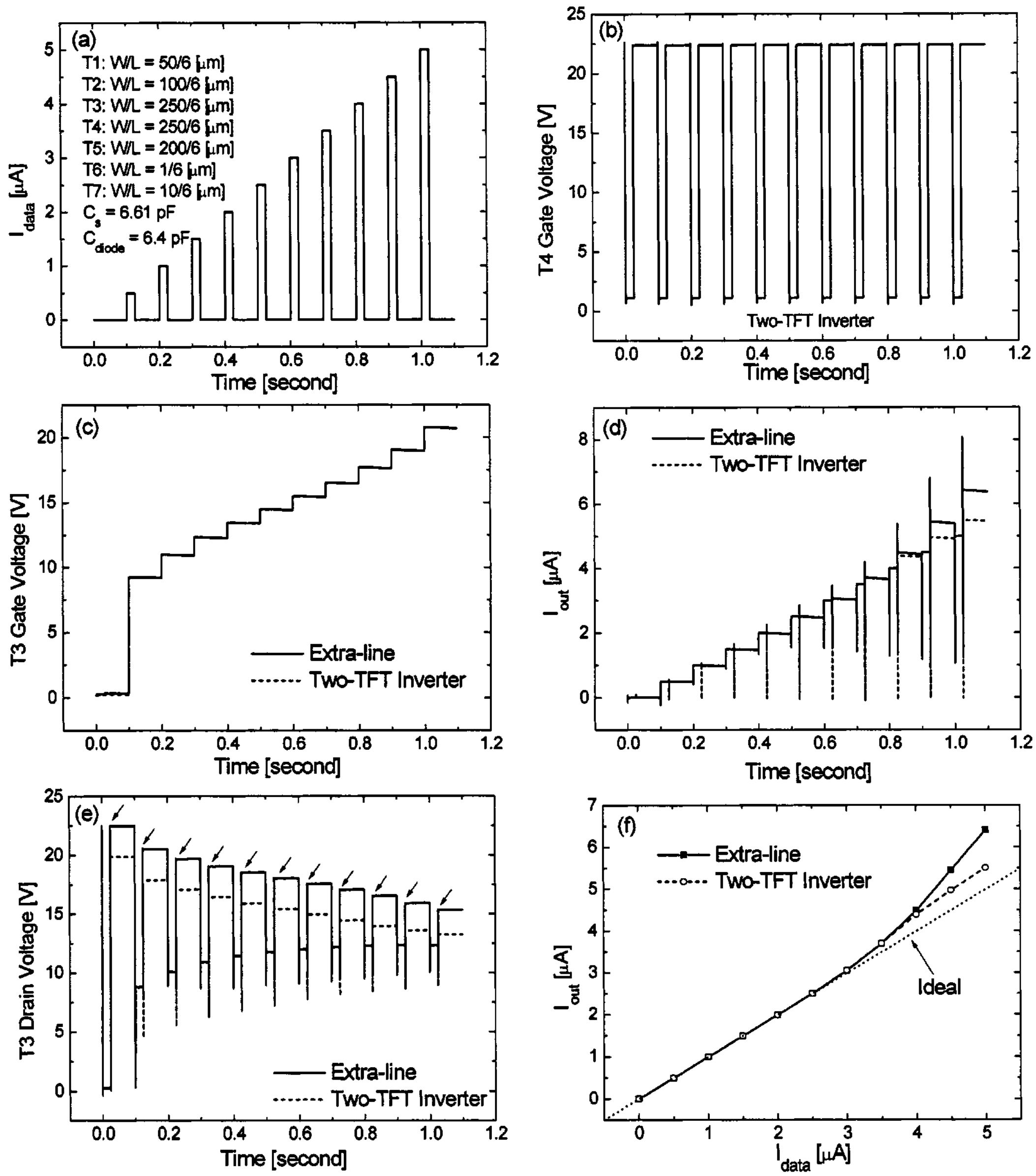

Fig. 2. Transient simulation results for the two pixel electrode circuits. (a) The input data current signal, (b) T4 gate voltage, (c) T3 (drive TFT) gate voltage, (d) output current, (e) T3 drain voltage as functions of time, and (f) output current versus input data current characteristics.

the TFT parasitic capacitors (C_p) were set at 570 fF, about an order of magnitude higher than the typical values in order to achieve simulation convergence.

Fig. 2(a)–(f) show the pixel electrode circuit simulation results for the two circuits. The circuits parameters used in the simulation are also listed in Fig. 2(a). The input data current pulse was increased from 0 to 5 μA with a step of 0.5 μA with a pulse width/interval $=$ 25/100 ms, as shown in Fig. 2(a). The select line signal (V_{select}) follows the same pulse width/interval with a fixed pulse amplitude of 25 V. Fig. 2(b) illustrates the simulated output voltage of the two-TFT inverter. This voltage is also the T4 gate voltage. When the pixel electrode circuit is selected, i.e., $V_{\mathrm{select}} = 25$ V, T4 gate voltage is only $\sim$ 1.1 V, well below the threshold voltage ($\sim$2.5 V) of T4. Therefore, T4 is off. When the pixel electrode circuit is deselected, i.e., $V_{\mathrm{select}} = 0$ V, T4 gate voltage is $\sim$ 22.5 V. Hence, T4 is turned on to allow the current flowing through from the V_{DD} line. This result indicates that a good voltage inverting effect is achieved by the two-TFT inverter.

Fig. 2(c) shows the evolution of T3 (drive TFT) gate voltage as a function of time. The pixel electrode circuit simulation results indicate that only minor differences exist on T3 gate voltages between the extra terminal and inverter approaches as both curves overlap. Because of the use of large size storage capacitor, in both circuits, T3 gate voltages remain almost unchanged in the OFF-state in a time interval of 100 ms. The T3 gate voltage decreases a little after pixel electrode circuit switching. This is due to the effect of parasitic capacitor.

The simulated output current characteristics shown in Fig. 2(d) indicate that the saturation effect of the output current levels observed previously [5] can be avoided in these circuits. An output current of several μA can be easily achieved for both the extra terminal and inverter pixel electrode circuit approaches.

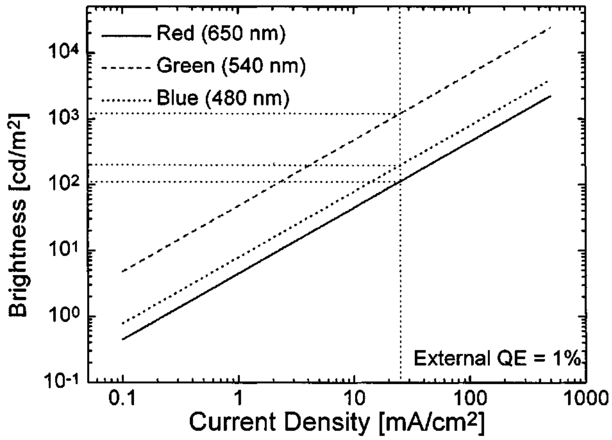

Fig. 3. OLED brightness as a function of current density for R, G, B emissions saturated at 650 nm, 540 nm, and 480 nm, respectively.

Fig. 2(e) shows the T3 drain voltage as a function of time. It clearly shows an increase of T3 drain voltage (pointed by arrows) after each pixel electrode circuit switching step, indicating that T3 indeed works in the deep saturation region $(V_{\rm DS} \gg V_{\rm GS} - V_{\rm th})$ and consequently, the output current level remains after each switching step.

In Fig. 2(f), the output current in the OFF-state is plotted against the input data current for both the extra terminal and inverter approaches. The results indicate that the output current is very close to the ideal case, and the output current level only differs less than 0.5% from the ideal case at the low current levels $(< 1\ \mu\text{A})$. Also excellent $I_{\rm out} - I_{\rm in}$ linearity was obtained, indicating that a good control of display gray level can be achieved with these approaches. At the same time, an output current level higher than 5 μA can be achieved in this pixel electrode circuit. For an 11-inch VGA full-color display with a pixel size of $\sim 100 \times 200\ \mu\text{m}^2$, this current level is equivalent to a current density of $25\ \text{mA/cm}^2$. Assuming the OLEDs with external quantum efficiency of 1%, the display brightness of $\sim$ 110, $\sim$ 1200, and $\sim 200\ \text{cd/m}^2$ for red (650 nm), green (540 nm), and blue (480 nm) emission respectively, can be achieved, as in Fig. 3. These values have been calculated using the following equation:

$$L = 683E(\lambda)\eta_{\rm ex}\frac{hc}{\pi\lambda}\frac{J}{e}$$

where

- L brightness;
- $E(\lambda)$ applied current density;
- J applied current density;
- $\eta_{\rm ex}$ brightness;

The calculated brightness values are sufficient for most portable display applications.

IV. Conclusion

In conclusion, we have developed two improved pixel electrode circuits based on four a-Si:H TFTs. We have shown that this circuit can provide a good linearity between the output and input currents. These pixel electrode circuits are expected to have both good electrical reliability and high output current level that is sufficient to achieve a pixel brightness of $\sim 1200\ \text{cd/m}^2$ for green emission (540 nm). Therefore, these circuits are ideal for the portable AM-OLEDs.

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